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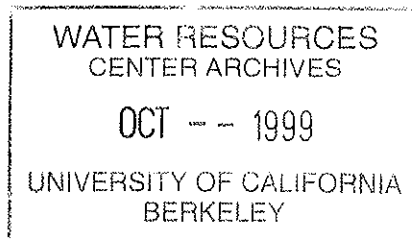
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ABSTRACT

Riparian vegetation is widely thought to stabilize stream banks, but this effect has rarely been quantified. We evaluated how riparian vegetation affects bank erodibility along the South Fork of the Kern River at Monache Meadow. Our methodology combines remote sensing estimates of bank migration rates with field measurements of bank strength. Our results demonstrate that vegetation communities significantly affect bank erodibility of a meandering montane meadow stream.

The South Fork Kern River at Monache Meadow is an ideal location for studying vegetation effects on bank erosion. The streambank soils are relatively homogenous, but are colonized by two distinct vegetation communities: a dry meadow community dominated by sagebrush and non-native grasses, and a wet meadow community dominated by rushes and sedges. We measured rates of channel migration in the wet meadow versus dry meadow by analyzing four decades of aerial photographs. Over 40 years, the stream channel migrated laterally up to 100 meters in the dry meadow, but less than 10 meters in the wet meadow. We used these measurements in combination with a numerical model of flow to calculate an erodibility coefficient that characterizes bank migration potential independent of channel curvature.

To complement this remote sensing analysis, we made field measurements of channel geometry, bed and bank material grain size, and the in-situ strength of vegetated bank soils. Measurements of how bank shear strength varies with vegetation community and density enabled us to use geotechnical models of bank stability to assess modes and frequencies of bank failure. By increasing the tensile strength of bank soils, wet meadow riparian vegetation increases the stable width of an undercut bank by a factor of 10. In-situ stabilization of failed blocks by wet meadow sedges and rushes limits the frequency of block failure and removal to approximately one in five years, as opposed to up to 10 failures per year in the dry meadow.

We assessed the impact of channel incision on bank stability. Our analysis of flood frequencies and flow depths using the HEC-RAS model compared pre- and post- incision patterns of bed shear stress and overbank flow. We observe a correlation between vegetation communities and stream characteristics, including bank height and frequency of overbank flows. We hypothesize that channel incision may convert wet meadow to dry meadow, with significant impacts on streambank stability.

Keywords: Meadows (1450), riparian vegetation (1985), rivers (2000), streams and stream dynamics (2300), wetlands (2730), fluvial processes (0955).

PROBLEM AND RESEARCH OBJECTIVES

We aim to quantify how bank erodibility varies with the presence or absence of herbaceous riparian species. The South Fork Kern River at Monache Meadows is an ideal location for studying vegetation effects on bank erosion. Monache Meadows is located on the Kern Plateau of the southern Sierra Nevada (elevation 2393m) (Figure 1). The South Fork of the Kern at Monache Meadows drains a 380 km² watershed that overlaps the boundary of the Inyo and Sequoia National Forests. The soils along the river channel are relatively homogeneous, but are colonized by two distinct vegetation communities: the northern reach is dominated by sagebrush (*Artemisia* spp.) and non-native annual herbs, while the southern reach is dominated by wet meadow vegetation including sedges (*Carex* spp.) and rushes (*Scirpus* spp, *Juncus* spp.).

Our primary objective is to assess whether rates and processes of stream migration, as indicators of bank stability, vary with vegetation type. Channel migration may be readily estimated from aerial photographs using Geographic Information System (GIS) software. However, lateral migration rates measured at different locations cannot be compared without taking the effects of stream curvature into account. For example, in homogeneous valley alluvium, curved bends tend to migrate more quickly than straight reaches. Previous researchers argue that rates of migration should generally increase with bend curvature, until a threshold is crossed where the bend is so tight that the flow velocity decreases (Hickin and Nanson 1984). However, the velocity distribution of streamflow within a bend (and thus the distribution of stresses on the banks and bed) depends not only on the geometry of the bend itself, but also on the curvature of the channel above the bend.

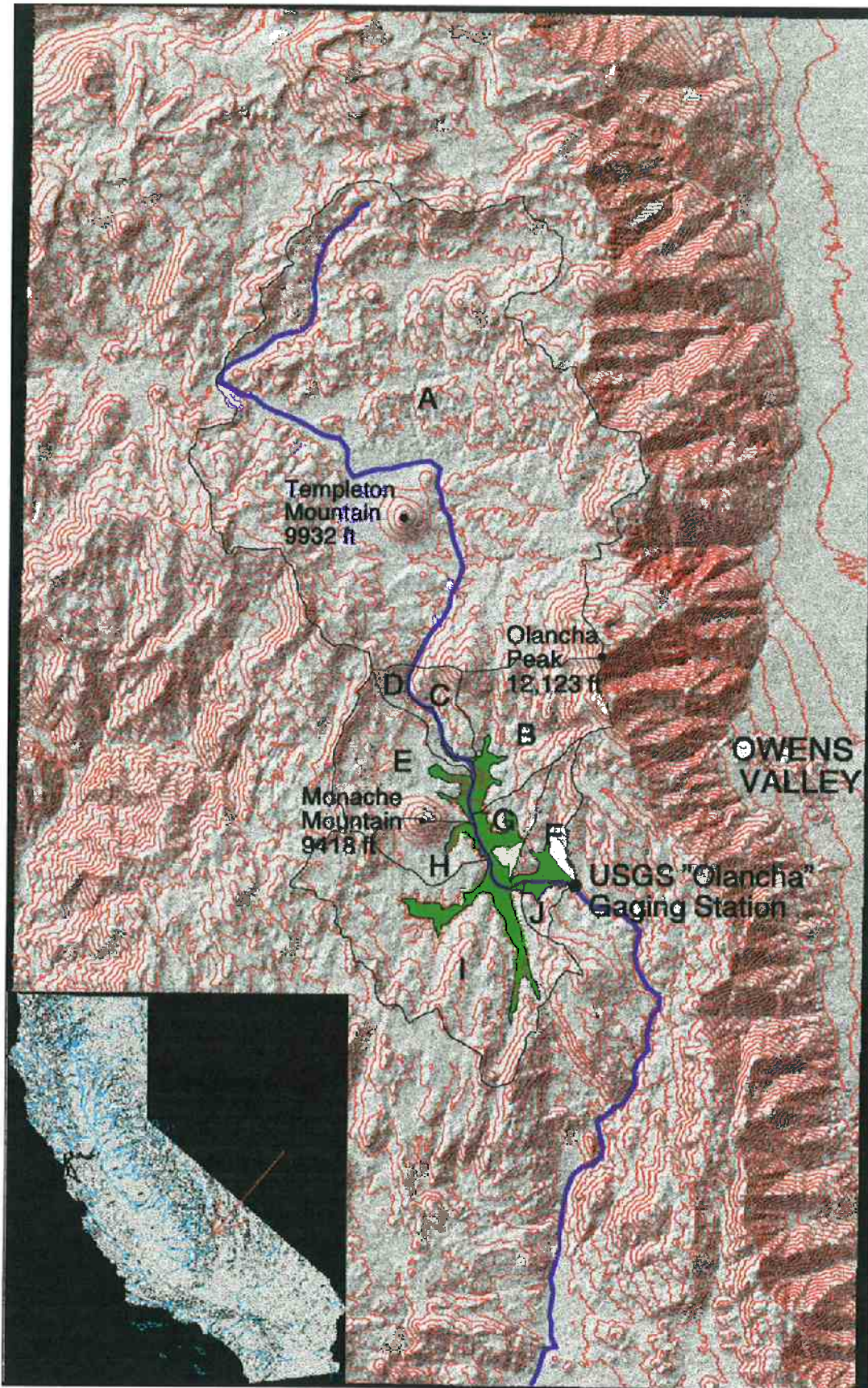
To account for the effects of channel curvature, we convert our migration measurements to estimates of bank erodibility using a numerical model of streamflow in bends developed by

Ikeda et al. (1981) and Johanneson and Parker (1989). The model estimates the velocity distribution in a meandering stream based on its channel geometry, its discharge, and the local and cumulative effects of its centerline curvature. We use the estimated velocity profiles for individual bends to normalize their measured migration rates, converting them to erodibility coefficients that quantify the relative susceptibility of each bend to erosion and migration. By comparing these erodibility coefficients for bends with dry meadow and wet meadow vegetation, we can quantify the effects of different bank materials on bank erodibility.

Our secondary objective is to explain how vegetation contributes to bank stability. We explore potential mechanisms of bank stabilization by measuring how bank shear strength varies with vegetation density. We use these shear strength measurements to predict the size of the failure blocks that are generated when the bank collapses. Combining failure block dimensions with the observed migration rates, we can estimate the frequency of bank failure for the two different vegetation types. We hypothesize that herbaceous riparian vegetation increases stable block dimensions and stabilizes failed blocks in place, thus slowing rates of bank failure and channel migration.

Our final objective is to explore the implications of channel incision for bank stability. Local botanical studies that show that sedges and rushes cannot become established on surfaces 0.75 meters or more above the groundwater table (Saar 1995). At Monache Meadow, channel incision may have depressed the local water table and precipitated a conversion of herbaceous wet meadow to dry sagebrush meadow. U.S. Forest Service personnel provide anecdotal evidence of bed degradation over the last 25 years (Dell Hubbs pers. comm.). We estimate the magnitude of incision and simulate effects on the extent of valley inundation (and by inference, shallow groundwater availability) using the HEC-RAS step-backwater model of flow.

Figure 1. Site Location - South Fork Kern River Watershed, Inyo and Sequoia National Forests, California



- F Watershed Subbasin
- Watershed Boundaries
- South Fork Kern River
- 100 m Contour Lines
- Monache Meadows

5 0 5 10 Kilometers

METHODOLOGY

Lateral Migration Measurements

We scanned three sets of aerial photographs (dated 1955, 1976, and 1995) to map channel locations and measure rates of lateral migration. We established ground control points using a total station survey and rectified the digital images using ARC-INFO software (Farrington and Lauer 1997). Rectification reduced distortion due to lens and terrain effects, and consequently reduced spatial error (the difference between the actual and the mapped location of a feature) to plus or minus 5m, as opposed to errors up to 90 meters estimated for non-rectified images. Rectifying all three sets of images to the same base coordinates enabled us to overlay the three channel centerlines, and thus to measure lateral migration.

Our unit of migration measurement is the “eroded area polygon” created by intersecting stream segments from two different years. We measure lateral migration as the average distance migrated for a length of stream defined by the eroded area polygon (figure 3). The average amount of lateral migration is thus equal to the polygon area divided by one-half of the polygon perimeter.

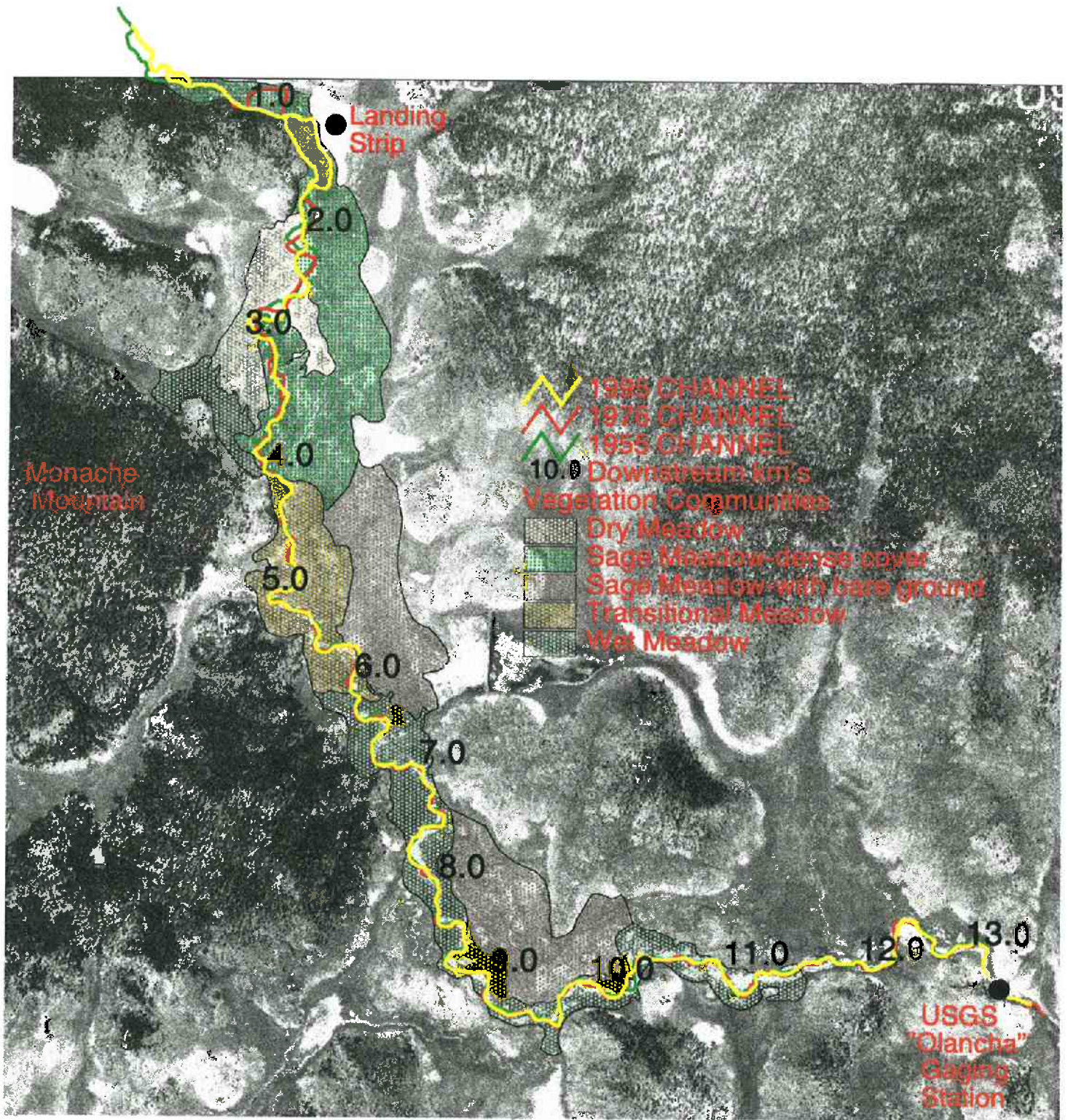
The “eroded area polygon” method avoids qualitative judgments required to apply alternative migration measurement methods. For example, methods such as tracking the apex of a bend or Hickin orthogonal mapping requires definition of arbitrary axes to serve as a measurement baseline: at Monache Meadows this baseline would have to shift orientation for each bend.

The limitation of the eroded area polygon method is that it only measures migration where some erosion has occurred: bends which have remained absolutely stable, expressing zero migration, are not included in a reach average. Therefore, the eroded polygon method may be considered a measure of the minimum extent of migration. At Monache Meadows, this limitation does not bias our results because every bend experienced some migration over the study period. However, polygons narrower than our spatial uncertainty in channel location ($\pm 5\text{m}$) were not analyzed.

Vegetation Mapping

We mapped vegetation using a series of 1994 color photographs (scale 1:2000) to define vegetation image “signatures” (the pattern and color saturation of a feature on a digital image) for the 1995 black and white aerial photograph. We ground-truthed the vegetation maps during the 1996 and 1997 field seasons. Five vegetation map categories (figure 2) divide the meadow into two primary zones: the dry meadow zone, including “Sage Meadow-dense cover” and “Sage Meadow—with bare ground” (both dominated by *Artemisia* spp.), and “Dry Meadow” (dominated by non-native annual herbaceous species) and the wet meadow zone, including “Wet Meadow” and “Transitional Meadow” both dominated by sedges (*Carex* spp.) and rushes (*Scirpus* spp.). All categories are impacted by cattle grazing. The transitional category identified on the 1995 photograph was identified in the field as a low-saturation wet meadow community, with patches of non-native annual herbaceous species. Examination of the 1955 photographic image suggests that this “Transitional Meadow” area was saturated wet meadow over 40 years ago, leading us to consider it as a “de-watered” wet meadow.

Figure 2. Map of vegetation communities and historic channels of the South Fork Kern River at Monache Meadows, CA



1 0 1 2 Kilometers



AERIAL PHOTO DATE: SEPTEMBER 30, 1995

Erodibility Coefficient Calculation

To normalize our lateral migration measurements for variations in channel curvature from bend to bend, we used a mathematical model for flow in a meandering stream developed by Ikeda et al. (1981) and Johanneson and Parker (1989). Larsen (1995) adopted this model to explain observed migration patterns on the Mississippi River. This model uses a perturbation expansion on curvature in the equations of motion for flow to estimate linear cross-stream profiles for bed elevation and depth-averaged flow velocities (figure 4). The model assumes that discharge, width, average depth, and slope are constant over the modeled reach. Although the model velocity estimates are approximate at best, based on a review of the literature we believe this is the best numerical tool available to assess the effects of curvature given the spatial resolution of our channel geometry data.

We used the following input parameter values to apply the Johanneson-Parker model to the South Fork of the Kern River: discharge of 20 cubic meters per second, bank height of 1.5 meters, channel width of 30 meters, median grain size of 4 mm, and an average slope of 0.001.

Johanneson and Parker (1989) argue that rates of meander migration should be proportional to the perturbation (U') from the mean velocity due to the acceleration of flow at the outside of a curved bend (figure 5). This approach assumes that if depth-averaged velocities increase linearly across the channel, U' should represent the magnitude of shear forces on the bank. If U' approximates the bank shear forces, we can use it to define an "erodibility coefficient" that expresses the vulnerability of the bank to shear forces imposed by the flow, such that:

$$M = E_o U'$$

where M is the bank migration rate, E_o is the erodibility coefficient, and U' is the cross-stream velocity perturbation (the difference between the velocity along the outside bank and the mean velocity). Because M and U' are both velocities, the erodibility coefficient E_o ,

$$E_o = M/U'$$

is dimensionless if M and U' are measured in the same units. Dimensionless values of E_o are small (on the order of 10^{-7}), since the average rate of bank migration is typically many orders of magnitude slower than the velocity of streamflow.

U' values are calculated at points spaced 0.5 channel widths along the channel centerline. We selected sets of U' values located within each sampled bend's "eroded area polygon." The maximum velocity perturbation (labeled U'_{max} in figure 3) for the bend was used to divide the migration measurement derived from the "eroded area polygon" to calculate an E_o value for the bend. To graph our results, we defined bend locations as the downstream distance coordinate of the midpoint of the eroded area polygon.

Field Survey

In the summers of 1996 and 1997 we completed a field survey to measure stream channel topography, exposed bank stratigraphy, bed material grain size, and bank strength (described below), and to ground truth our maps of the vegetation communities. The stream channel geometry was measured using a total station survey. We mapped bank stratigraphy at cut banks and tested major units for cohesion using a Torvane and penetrometer. Bed material grain size was measured using pebble counts and sieves.

Figure 3. Eroded Area Polygon

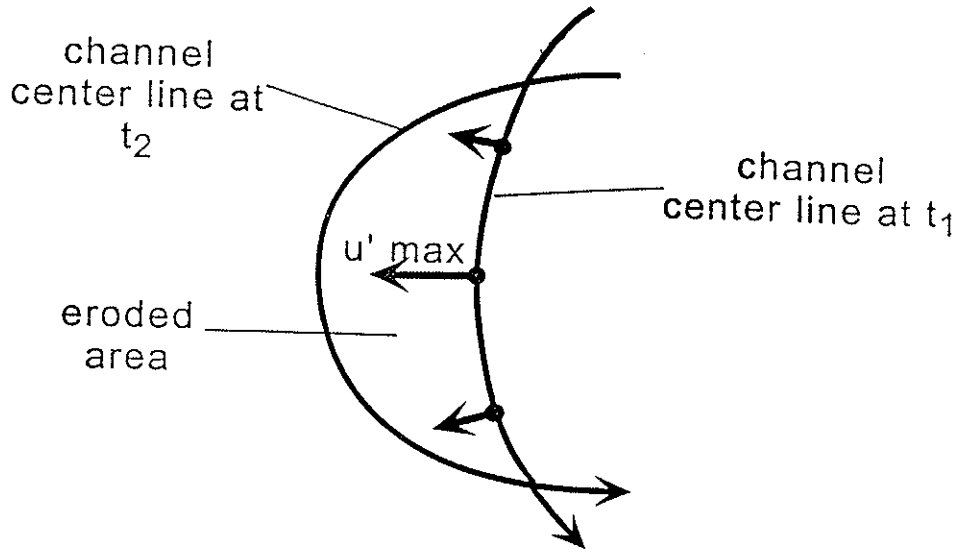


Figure 4. A Linear Estimate of Cross-Stream Velocities

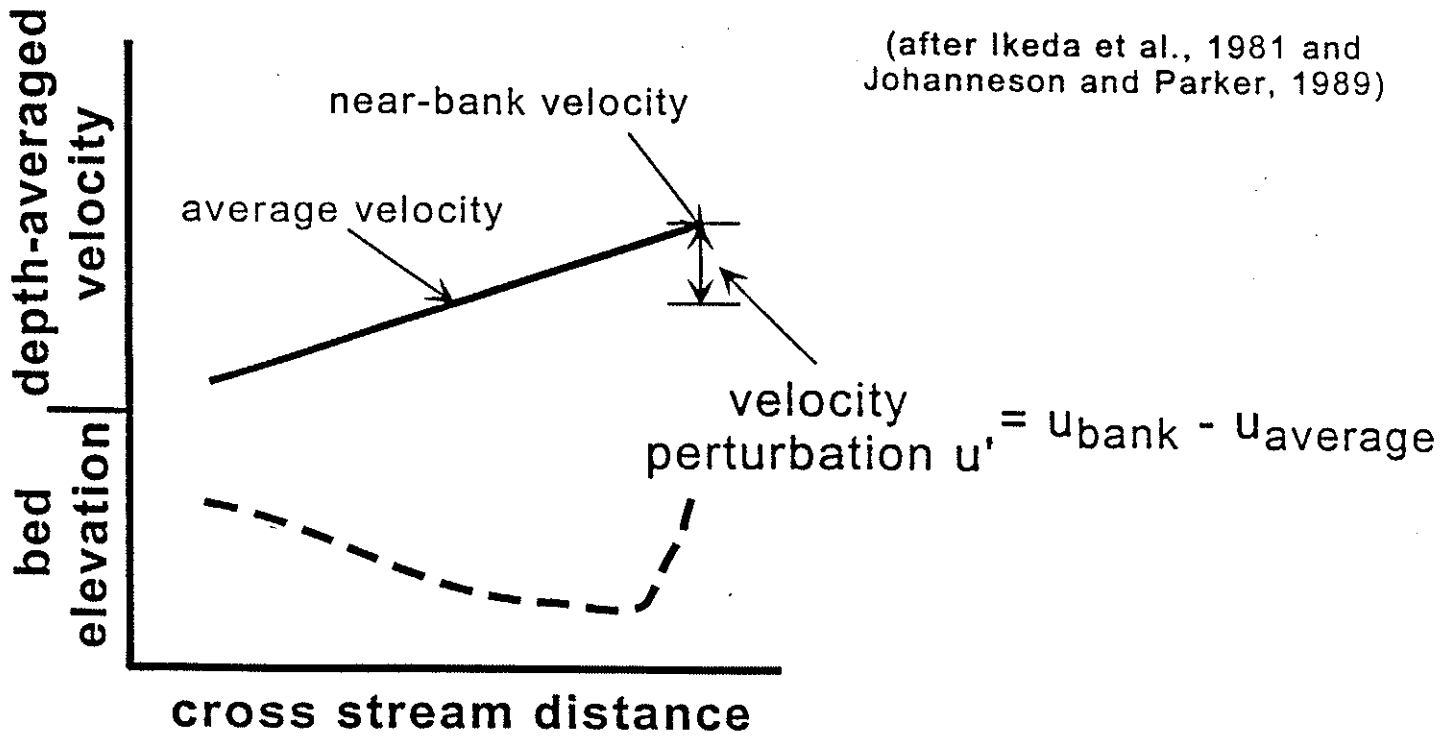
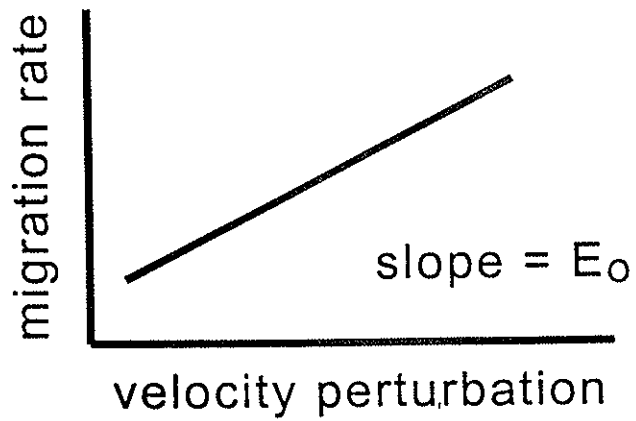


Figure 5. Erodibility Coefficient Calculation

$$M(\text{migration rate}) = E_o \times u'(\text{velocity perturbation})$$



$$E_o = \frac{M \text{ (m/s)}}{u' \text{ (m/s)}}$$

(after Johanneson and Parker, 1989 and Larsen, 1995)

Vegetated Bank Material Shear Strength Measurements

We used a geotechnical shear vane to measure the in-situ strength of vegetated bank materials. As opposed to the shallow-bladed Torvane (blades approximately 1cm deep) typically used for rapid assessment of soil cohesion, we selected a large ASTM-standard geotechnical shear vane with rectangular blades (penetrating to a depth of a 40 cm with a vane radius of 16 cm). This vane size and configuration was selected as the best option to test the strength of soils reinforced with the dense fibrous root networks typical of rushes and sedges. These root networks are primarily comprised of very fine roots with diameters 1 mm or less and display root area ratios (the ratio of total root area to total root plus soil area for a planar exposure of bank soil) of up to 50 percent.

To measure vegetated bank material shear strength, we first removed all above-ground vegetation from a 16 cm diameter circle around each shear strength test location. Vegetation was clipped to within 0.5 cm of the ground surface and stored in plastic sample bags. Stem counts were completed on site. Vegetation samples were bagged, dried and weighed to measure above ground biomass per unit area.

After the vegetation was removed, the vane was pounded into the center of the cleared circle. Torque was applied to the sample using a handle perpendicular to the vane's central axis. The magnitude of applied torque was measured using a spring scale and converted to soil shear strength according to the ASTM protocol. Following the engineering standard, failure is defined to occur at the moment when applied torque reaches a maximum. After that point, the soil is weakened and applied torque rapidly decreases as the sample begins to rotate within the cylinder defined by the vane blades. In testing vegetated material, failure appears to be associated with pulling out and/or breaking roots that bind the soil sample.

The majority of strength measurements were made at two types of sites: 1) sedge- and rush-colonized bar surfaces comprised of sorted sand and gravel (generally located at the inside of dry and wet meadow bends), and 2) sedge-colonized failed slump blocks where the local substrate constituents include terrace soil, dense root networks, trapped fluvial gravels, and decaying organic matter (generally located at the outside of wet meadow bends). The majority of samples were located within 30 cm of the water surface and were at or near saturation. Saturation is the likely condition at bank failure, because failures tend to be most frequent on the falling limb of the hydrograph (Lawler 1995). Only a few of the failed terrace blocks that were colonized by sagebrush were still intact and located close enough to the water surface to be near saturation.

At several locations, below-ground soil and root samples were excavated after strength testing. The samples were wet sieved to separate roots from soils. Roots and soils were dried to measure below-ground biomass and soil mass.

HEC-RAS Analysis to Assess Incision Effects on Bank Stability

We computed one-dimensional, steady-state, water surface profiles using the Army Corps of Engineers HEC-RAS model (U.S. Army Corps of Engineers 1997). This routine employs an iterative procedure that solves the energy equation, a modified form of Bernoulli's equation which accounts for head losses due to friction. The model inputs include cross-sectional channel geometry, distance between cross-sections, and Manning's roughness coefficients (which are used to calculate flow depths for a given channel cross-section). We applied the HEC-RAS model for three purposes: 1) to generate a "back-of-the envelope" estimate of the extent of channel incision, 2) to estimate longitudinal variations in bed shear stress, and 3) to model patterns of valley inundation before and after channel incision.

The HEC-RAS model complements the Johanneson-Parker linear velocity model (1989) used to calculate erodibility coefficients. The linear velocity model addresses the effects of curvature but assumes constant slope. The HEC-RAS model effectively estimates how gradual changes in channel slope may affect flow depths, and in turn, bed shear stresses, which also serve to destabilize channel banks.

We performed a discharge frequency analysis for the Olancha gage located at the base of Monache Meadows (elevation 2376m). Since the continuous discharge record for the Olancha gage is only 11 years in length, we extended this record using data from the Onyx gage located 45 miles downstream on the South Fork of the Kern River (elevation 878m), which has a continuous discharge record 47 years in length (Salas 1980). The correlation coefficient for peak flows and mean annual flows at the two stations were 0.82 and 0.89 respectively. The purpose of extending the Olancha record with the Onyx record was to reduce the statistical error inherent in extrapolating flood discharge frequencies based on a very short record. The extended Olancha gage record was plotted using Log Normal and Log Pearson III probability distributions to estimate flow recurrence intervals (Dunne and Leopold 1978). We selected stream discharges with recurrence intervals of 1.5, 2, 5, 10, 50, and 100 years as inputs to the HEC-RAS flow analysis.

To estimate the flow rate as a function of downstream distance, we assumed that equal watershed areas contribute equal flow volumes to the river. Reach flow was therefore estimated by multiplying discharge for a given recurrence interval (table 4) by a ratio of the upstream

watershed area to total watershed area for a given channel reach. We selected a Manning's roughness coefficient of 0.042, a first estimate for both the brushy floodplain and the winding channel with heavily vegetated banks found at Monache Meadows (Roberson and Crowe, 1993). Cross sections were extended as a flat surface from the edge of the river channel and were then abruptly joined to the 7880 foot (2401 m) contour line (which rings the meadows on the USGS quad) to allow estimation of the lateral extent of floodplain inundation.

We ran the HEC-RAS model on the South Fork Kern River at Monache Meadows for both the 1997 channel geometry and for a hypothetical unincised channel. The dimensions of this “unincised channel” were based on the volume required to carry the two-year return interval flow, and on the principles of hydraulic geometry. We selected a width to depth ratio of 18 to 1 based on the geometry of the channel at the Olancha gage (Collins 1995). We calculated bed shear stresses from HEC-RAS-generated flow depths using the following equation:

$$\tau = \rho g h S$$

where τ is bed shear stress (Pa), ρ is water density (N/m^3), g is gravitational acceleration (m/s^2), h is the flow depth (m), and S is the water surface slope (Dingman, 1984).

RESULTS

Lateral Migration Rates and Bank Erodibility Coefficients

A map of historic stream channels and vegetation communities, superimposed on a 1995 photographic image, is shown in figure 2. This figure shows qualitatively that channel migration is more pronounced in the dry meadow vegetation communities (0 to 4000m downstream distance, Sage and Dry Meadow map categories) than in the wet meadow communities (4000 to 7000m downstream distance, Wet Meadow and Transitional Meadow map categories). Our lateral migration measurements quantify this difference.

We show how migration rates for selected bend “eroded area polygons” vary between the dry meadow (downstream coordinates 0 to 4000m) and the wet meadow (4000m to 8000m) in figure 6. We observe that the dry meadow reach migrated up to 3 m/y, while the wet meadow migrated on average 0.25 m/y, close to use our level of detection given spatial uncertainty. Similarly, erodibility coefficient calculations suggest an order of magnitude difference between dry and wet meadow (figure 7).

Table 1. Migration Analysis Summary

| Time Interval | Dry Meadow | | Wet Meadow | |
|---------------|-----------------------------------|---|-----------------------------------|---|
| | Average Migration Rate (m/y) ± SE | Erodibility x 10 ⁻⁷ (dimensionless) ± SE | Average Migration Rate (m/y) ± SE | Erodibility x 10 ⁻⁷ (dimensionless) ± SE |
| 1955-1976 | 1.3 ± 0.4 | 3.7 ± 0.5 | 0.23 ± 0.02 | 0.58 ± 0.02 |
| 1976-1995 | 1.6 ± 0.7 | 8.4 ± 0.7 | 0.25 ± 0.01 | 0.64 ± 0.03 |

SE = standard error

Average migration rates in the dry meadow reach are approximately six times greater than those for the wet meadow reach for both time intervals. Comparison of average erodibility coefficients for the two vegetation types reveals a greater contrast: once migration measurements are normalized for differences in channel curvature, the dry meadow reach is estimated to be on average 13 times more erodible than the wet meadow reach (1976-1995 time interval). The contrast between erodibility coefficients is greater than the contrast between migration rates, indicating that the wet meadow channel is less susceptible to migration despite greater flow shear forces acting on its banks.

The longitudinal profile and terrace elevations measured using the total station survey indicate that the bank heights are higher in the dry meadow than the wet meadow (figure 8). Plotting migration rates and erodibility coefficients against the bank heights of eroded area polygons (figures 9 – 11), suggests that banks over 1.0 m height are significantly less stable. In the following sections we will explore whether it is bank height alone or a combination of bank height and vegetation characteristics that control bank stability for this montane meadow.

Effects of Vegetation on Bank Shear Strength, Failure Modes and Rates

Figures 12 and 13 display a generally linear relationship between above ground biomass and vegetated bank material shear strength. Rush reinforcement of sand/gravel substrate (figure 12) is found to be significant at the 1% level, contributing 0.09 (\pm 0.01) kPa shear strength per g/m² biomass. Sedge reinforcement of failed slump blocks displays a 0.04 (\pm 0.01) kPa strength increase per gram above ground biomass. Our strength test results and field observations suggest that sedges are most effective at stabilizing slump blocks, where randomly oriented roots

Figure 6. Average Annual Migration vs. Downstream Distance

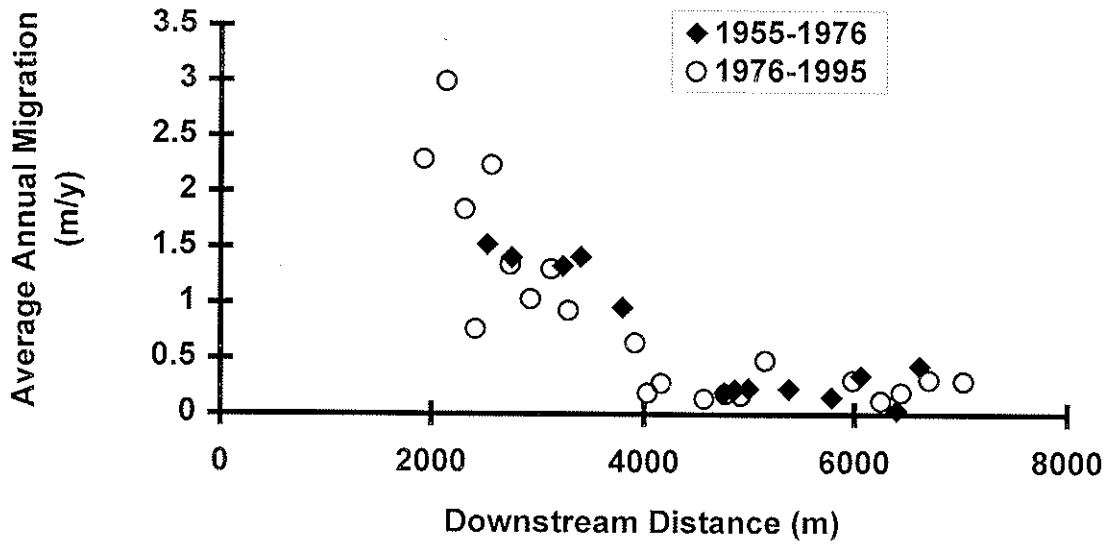


Figure 7. Erodibility Coefficient vs. Downstream Distance

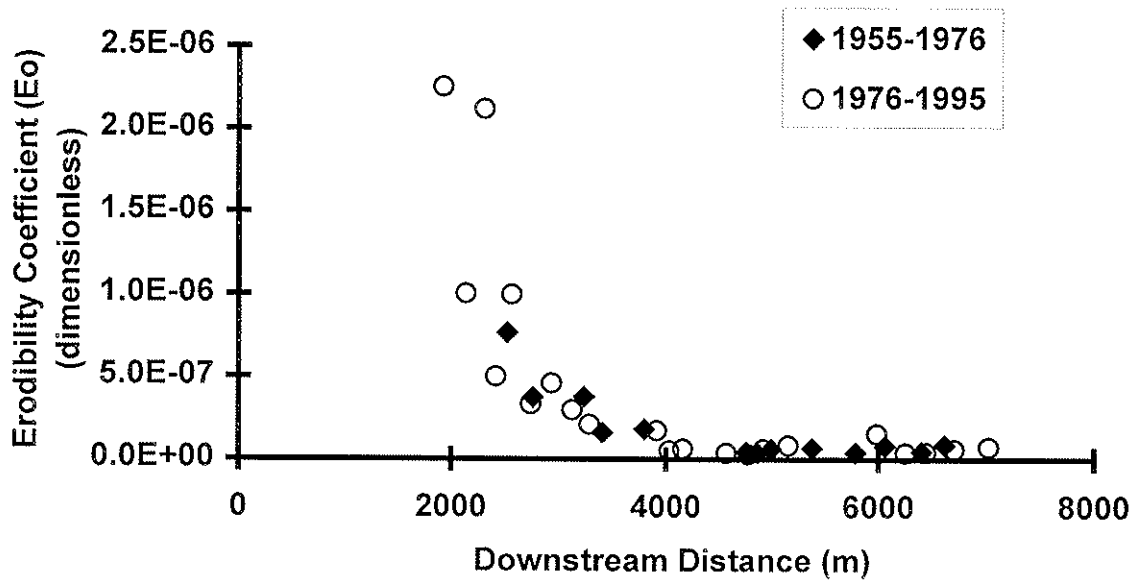


Figure 8. Longitudinal Profile and Relative Bank Height

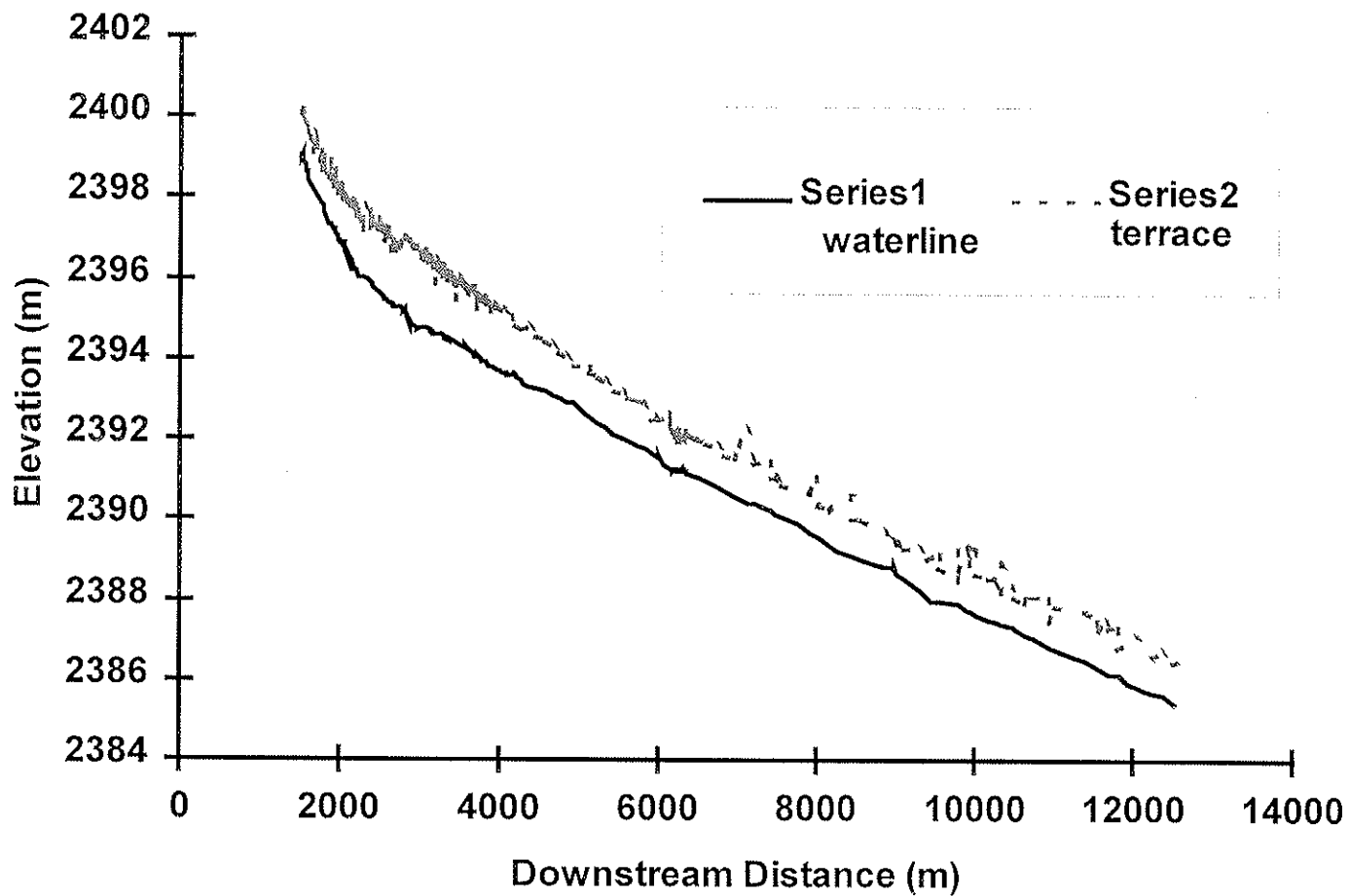


Figure 9. Bank Height vs. Downstream Distance

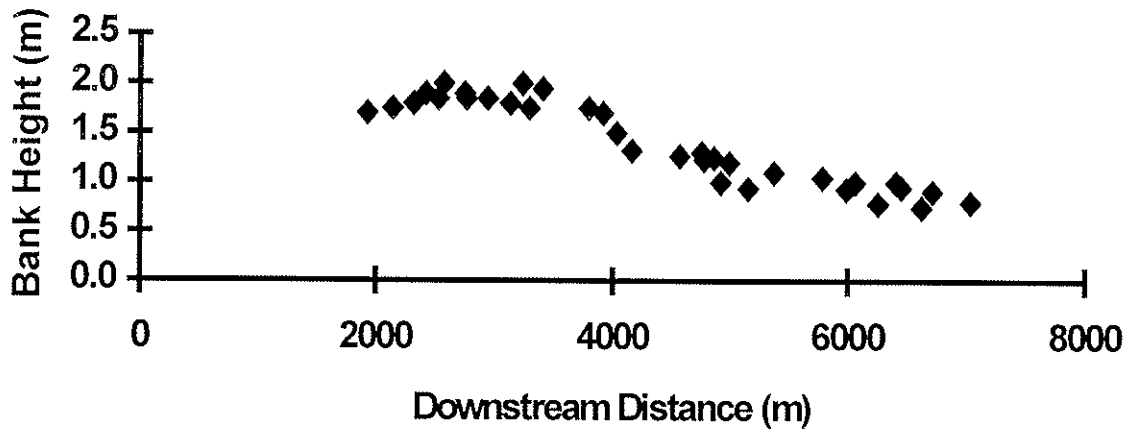


Figure 10. Average Annual Migration vs. Bank Height

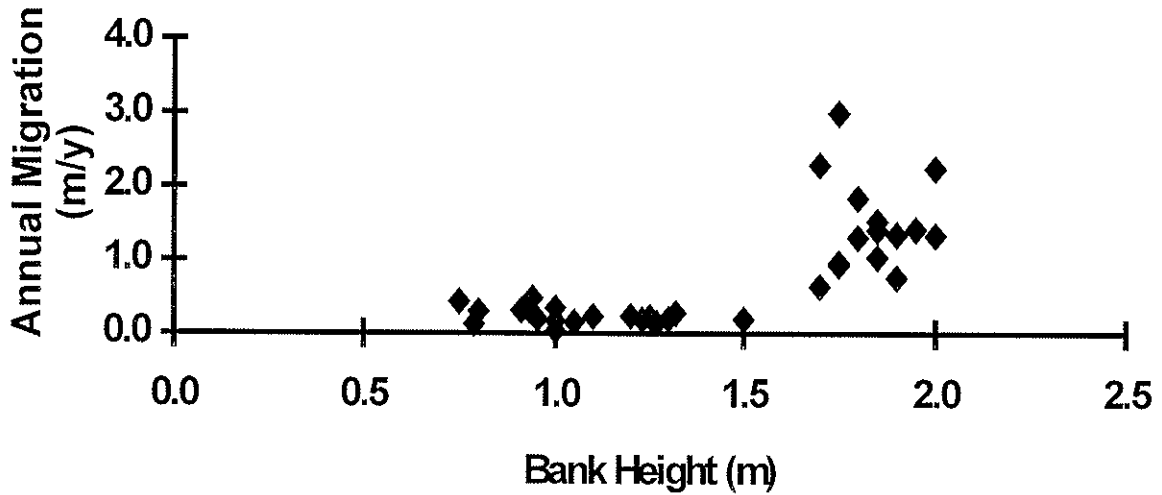
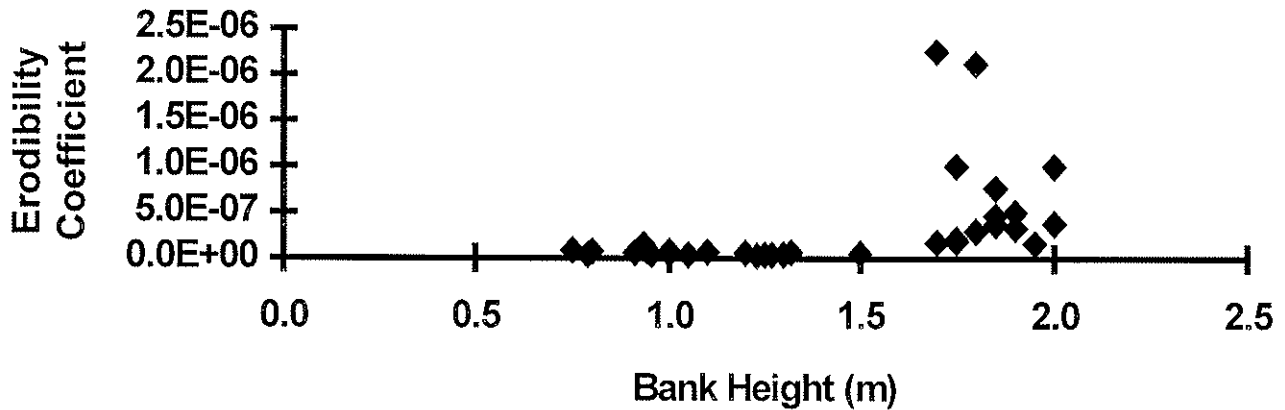


Figure 11. Erodibility Coefficient vs. Bank Height



generate a dense mat or “wad,” approximately 0.75 m thick, which is apparently the product of multiple seasons of growth. Sedge root wads often extend tens of centimeters below the active bed, which serves to reinforce the toe of the bank. Meanwhile, rushes appear more effective than sedges at stabilizing fresh bar surfaces, where the ability to rapidly generate long linear root elements serves to anchor plants in place during the dry season.

We collected above ground biomass as an indicator of the degree of root colonization. For a smaller number of samples we collected below ground roots and substrate to calculate the ratio of root to soil mass. Our analysis of figure 14 suggests that the root/soil ratio is a highly significant indicator of soil strength (significant at less than the 1% level), with soil strength increasing linearly with the root/soil ratio with a slope of 1020 (+/- 360) kPa per dimensionless ratio unit.

Only a few sagebrush colonized terrace blocks were available for sampling; their average strength is provided below. We did not sample above ground biomass of sagebrush because the extreme difference in plant morphology precluded a comparison with sedges or rushes. We noted visually that exposed bank soils displayed root area ratios of <5 percent, as opposed to up to 50 percent root area ratios observed for sedge and rush reinforced soils.

Table 2. Representative Bank Material Strengths

| Substrate | Bar (sand/gravel) | Terrace (fine sand) | Vegetated Bar (sand/gravel) | | Slump Block |
|---------------------------------------|----------------------|------------------------|--------------------------------|-------|----------------|
| | | | Rush | Sedge | |
| Vegetation | none | Sage | Rush | Sedge | Sedge |
| Average Shear Strength (kPa) | 5 | 15 | 46 | 38 | 43 |
| Average Biomass (g) | 0 | --- | 450 | 680 | 680 |

Figure 12. Shear Strength vs. Biomass:
Bar (Sand/Gravel) Substrate

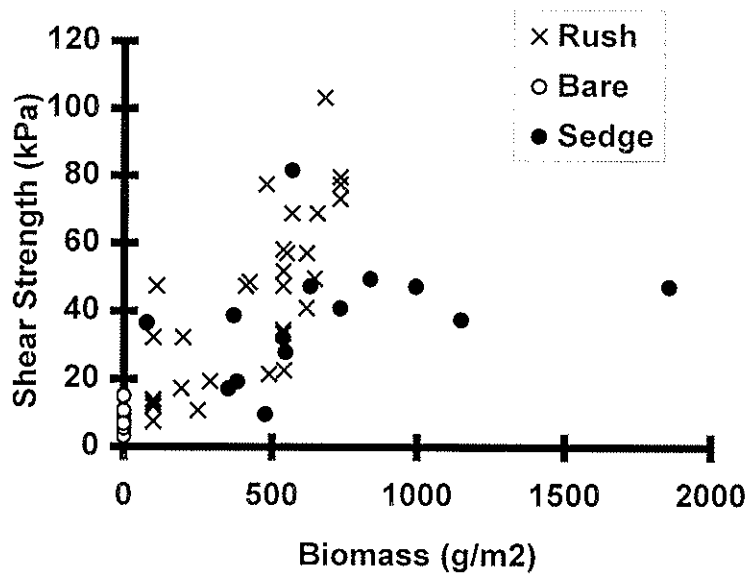
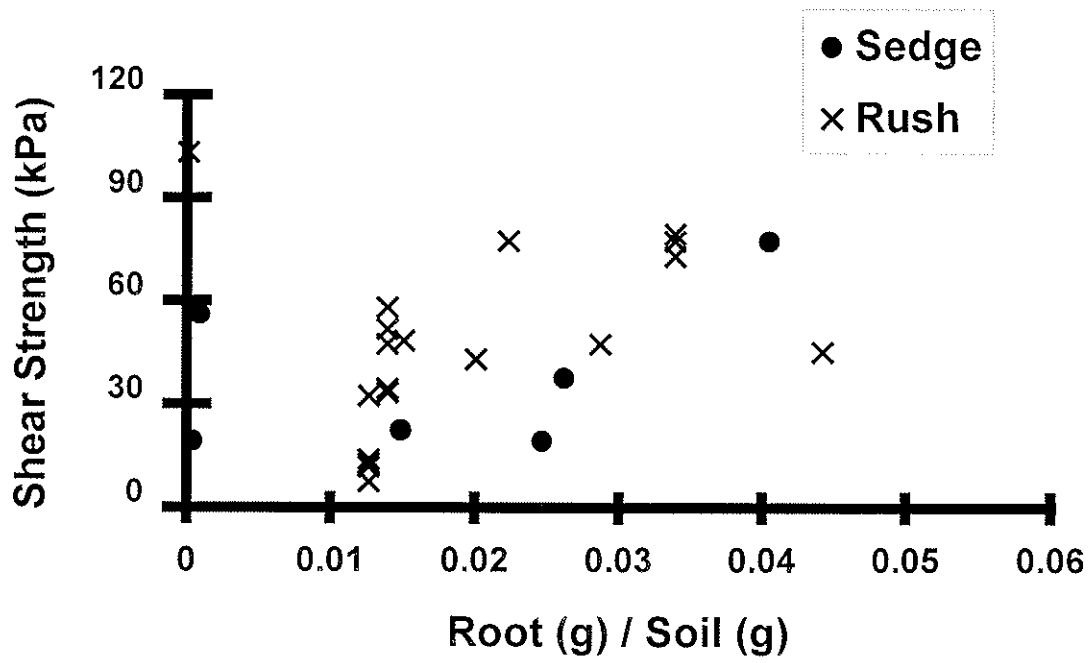


Figure 14. Shear Strength vs. Root Biomass/Soil Mass



Stability Analysis

Our field observations indicate that banks in both the dry and wet meadows tend to fail in cantilever mode. We estimated the likelihood of bank failure using a geotechnical model of cantilever bank stability developed by Thorne and Tovey (1981) and the representative strength values listed in table 2. Assuming that root strength contributes to the tensile rather than compressive strength of a soil, we calculated stable block widths for both the sagebrush and sedge dominated banks using the following relationship:

$$b = \sqrt{\frac{\sigma_T t^2 + \sigma_c c^2}{\gamma h}} \quad \text{given } h = c + t \quad \text{and} \quad \frac{\sigma_c}{\sigma_T} = \frac{c}{t}$$

where h = total block height, c = block height under compressive stress, t = block height under tensile stress, σ_T = tensile strength, σ_c = compressive strength, and γ = saturated bulk density.

The maximum width of a stable undercut bank block as estimated with the equation above agreed with our field observations; in the wet meadow reaches cantilevered overhang measured up to one meter. We divided average channel migration rates by predicted failure block widths to estimate a failure frequency for each reach.

Table 3. Stability Analysis

| | Dry Meadow | Wet Meadow |
|-----------------------------|--------------------|---------------------|
| Bank Shear Strength (kPa) | 15 | 45 |
| Stable Cantilever Width (m) | 0.13 | 1.00 |
| Bank Height (m) | 1.5 + | ~0.75 |
| Detachment Likely? | Yes | No |
| Failure Frequency | 10 failures / year | 1 failure / 5 years |

This stability analysis clarifies how three-dimensional bank erosion processes affect observed channel migration rates. Although dry meadow banks fail in smaller individual block units, the weakness of block materials, and the high ratio of bank height to block width, ensure that blocks become fully detached from the bank during failure. By contrast, the increased tensile strength of wet meadow soils facilitates formation of failure blocks up to eight times the width of dry meadow blocks. If it remains in place at the foot of the bank, the wet meadow block will reduce flow shear acting on the bank. Because wet meadow block width potentially exceeds the bank height, the risk of detachment after failure is low. Thus, the failed wet meadow block may stay in place and protect the bank from further erosion. Our failure frequency calculation indicates that an average of five years of flow is required to undermine and remove a wet meadow block, but only a few weeks are required to undermine and remove a dry meadow block.

Bed and Bank Material Grain Size

We measured bed material grain size at the downstream end of bar features to estimate the coarse fraction of bedload (figure 15). These measurements suggest that bars between 0 – 4000m downstream are composed of cobbles and gravels (median grain size 10-60 mm): below 4000m downstream the median grain size of bar materials is consistently less than 5mm. The active channel bed material at low flow was sorted sand of approximately 1mm grain size.

We mapped bank stratigraphy at exposed cut banks to see how terrace-derived bank material varied in the downstream direction. We also tested major strata with a Torvane and penetrometer to detect any variations in unvegetated material shear strength. These analyses were only applied to cut banks between 0-6300m downstream distance: after this point, banks

were composed of wet meadow substrate, with a soil matrix composed primarily of decaying organic matter and trapped fluvial gravels rather than terrace soils.

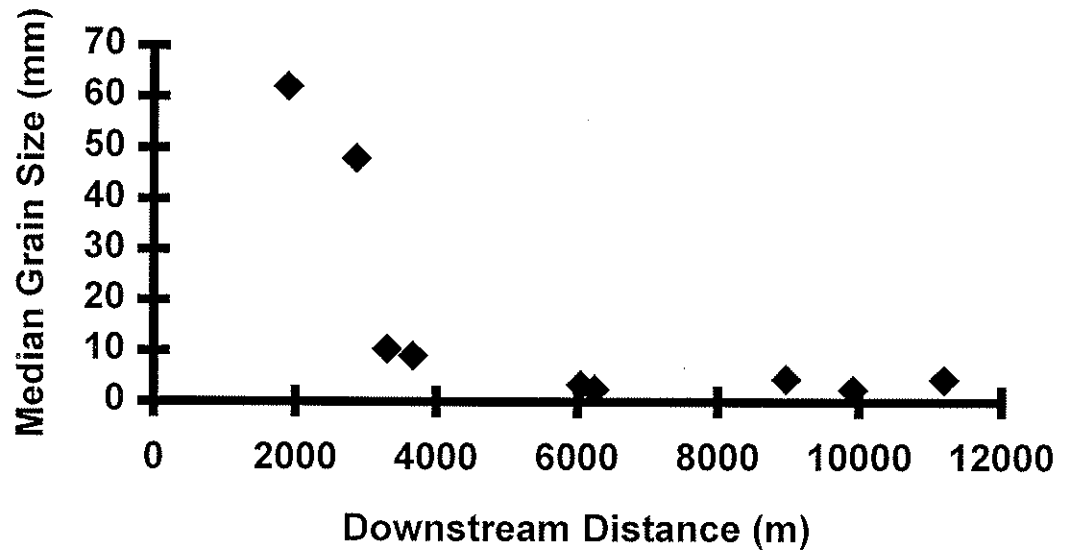
Exposed bank stratigraphy in the dry meadow did not significantly vary with downstream distance. Typical strata were comprised of fine to medium sands interbedded with silt-sand mixtures. A darker micaceous stratum with higher clay and organic content than surrounding layers occasionally emerged at a depth of 0.75 to 1.5m below the terrace surface. In the northern dry meadow reaches, this layer was sometimes underlain by a coarser gravel layer. The summary table below indicates that the strengths of un-vegetated bank measured using rapid assessment tools (the Torvane and penetrometer) show no clear difference between the wet and dry meadow communities.

Table 4. Unvegetated Bank Soils Analysis

| Downstream Distance (m) | 1400 | 2237 | 3300 | 3670 | 3975 | 4500 | 6290 |
|--|------|------|------|------|------|------|------|
| Torvane (instrument units) | 2.6 | 2.4 | 2.2 | 2.1 | 2.4 | 2.1 | 2.5 |
| Penetrometer (instrument units) | 1.3 | 1.4 | 1.7 | 1.3 | 1.8 | 1.3 | 1.4 |

The purpose of these bed and bank material grain size analyses was to see whether the variation in bank migration and erodibility could be attributed to increased bank soil cohesion or decreased bed mobility with downstream distance, rather than the transition from dry to wet meadow vegetation. These analyses indicate that bed and bank material variations, independent of vegetation influences on bank shear strength, do not explain measured variations in bank erodibility

Figure 15. Bed Grain Size vs. Downstream Distance



Flow Frequency Analysis

A 380km² watershed drains to the gage located at the base of Monache Meadows. This drainage area encompasses the headwaters of the South Fork of the Kern River and 51 km of main stem channel, 12 km of which is located within Monache Meadows. The watershed geology is primarily granitic, punctuated with andesitic volcanoes including Templeton Mountain and Monache Mountain. Approximately 70 percent of the watershed is relatively steep forest; the remaining 30 percent is flat alluvial meadow. The hydrologic cycle of the South Fork of the Kern River at Monache Meadows is dominated by snowmelt-driven peak flows which occur between March and June. The results of our flood frequency analysis are summarized below in table 5, with the extended gage record of annual peak flows plotted in figure 16. The Log Pearson III and the Log Normal distributions were averaged to calculate input values for the HEC-RAS analysis.

Table 5. Flood Frequency Analysis. South Fork Kern River at Monache Meadows, CA

| FLOW FREQUENCY | | | |
|------------------------------------|--------------------------------------|---|--------------------------------|
| Recurrence Interval (years) | Log Normal Distribution (cms) | Log Pearson III Distribution (cms) | Average Discharge (cms) |
| 1.01 | 16.0 | 47 | 32 |
| 1.5 | 250 | 250 | 250 |
| 2 | 398 | 377 | 390 |
| 2.3 | 447 | 450 | 450 |
| 5 | 707 | 770 | 740 |
| 10 | 1122 | 1109 | 1115 |
| 25 | 1698 | 1628 | 1665 |
| 50 | 2137 | 2080 | 2110 |
| 100 | 2692 | 2584 | 2640 |
| 200 | 3548 | 3150 | 3350 |

Figure 16. Extended Peak Annual Flow Record for the South Fork Kern River at Monache Meadows, CA. Olancha gage record (circles) extended with Onyx gage data (squares).

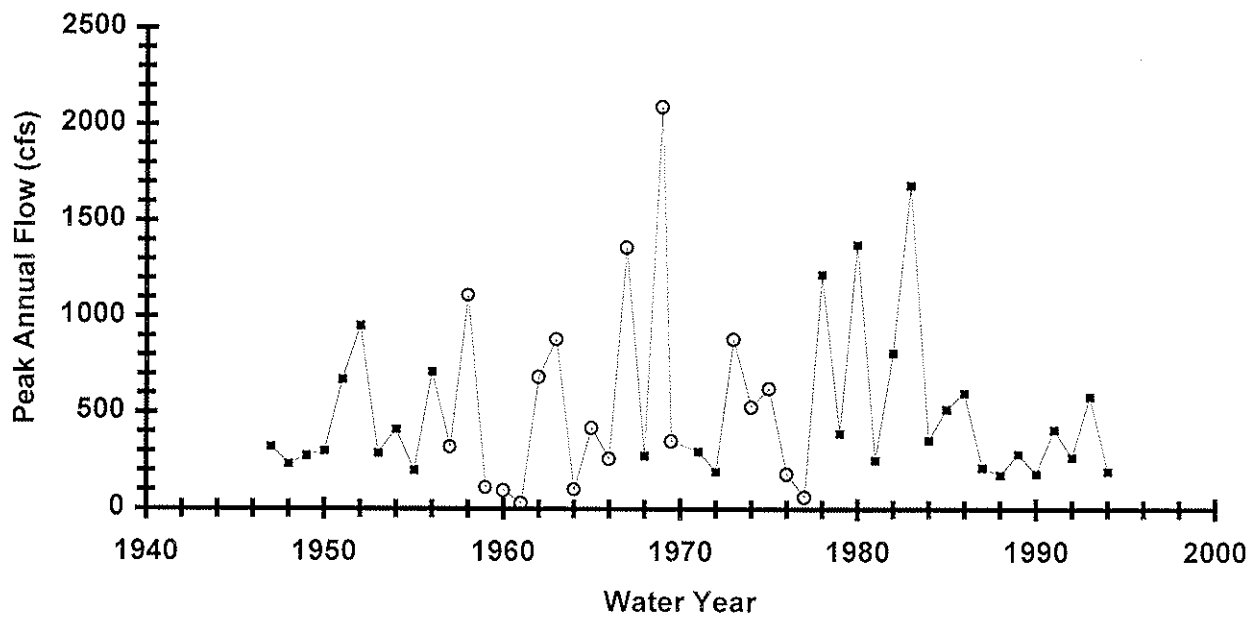
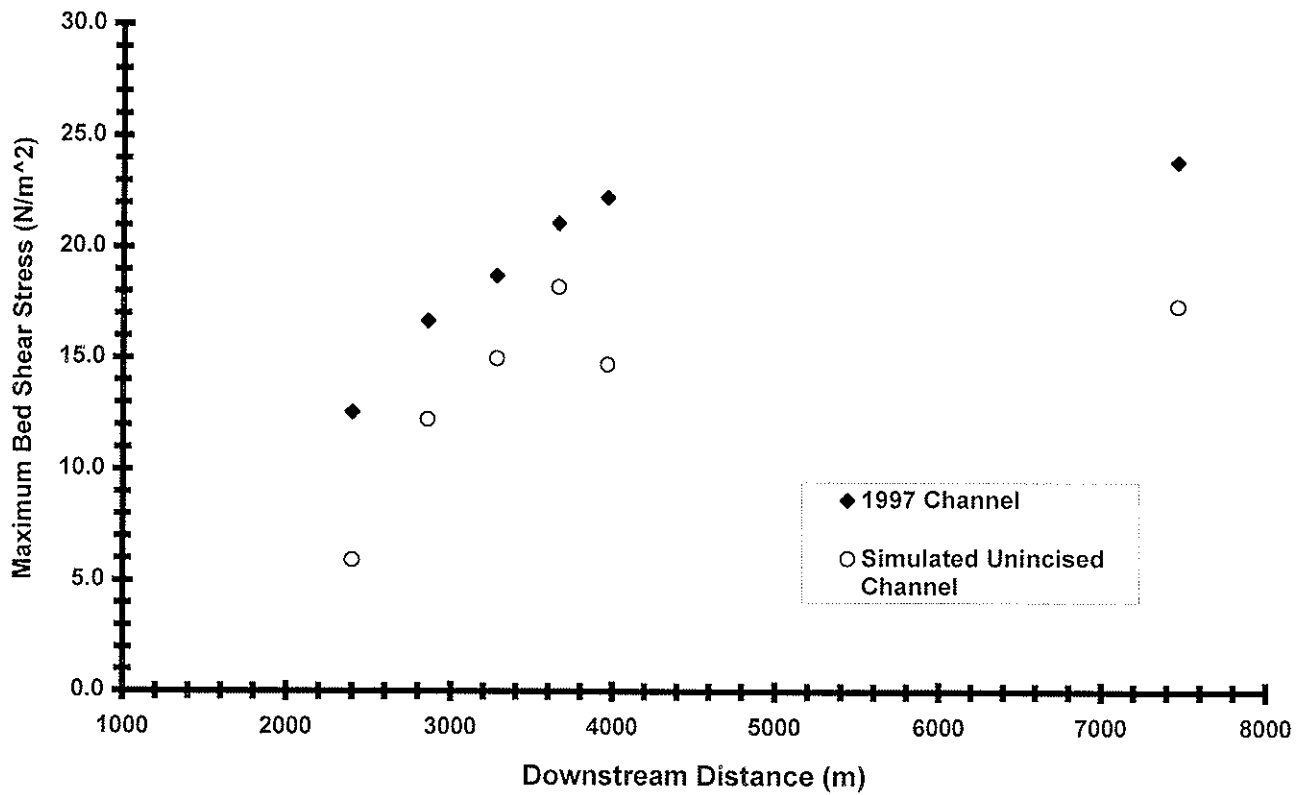


Figure 17. Bed Shear Stress vs. Downstream Distance for the 100-Year Flow



The extended gage record for the Olancha gage (figure 16) shows that the maximum recorded peak flow value of 2100 cfs occurred in water year 1969, which corresponds to a flow recurrence interval of approximately 50 years (see table 5 below). Between 1955 and 1976, 10 peak flows met or exceeded the two-year recurrence interval flow of 350 cfs. Between 1976 and 1995 the two-year flow was exceeded nine times. This suggests that our two time intervals were not highly dissimilar in terms of peak flow distribution, which may account for the consistent amounts of average migration over the two time periods (1.3 m/y and 1.6 m/y, respectively, for the dry meadow, and 0.23 m/y and 0.25 m/y, respectively, for the wet meadow).

Channel Incision Estimate

We ran the HEC-RAS model to estimate flow depths in two channels: 1) the existing channel surveyed in 1997, and 2) the simulated “unincised” channel designed to hold the two-year flow. This analysis essentially assumes that the two-year flow constitutes the formative “bankfull” discharge, a conservative value for estimating incision. For the 1997 channel geometry, the difference between the two-year flow depth and the existing bank height provides a very rough estimate of the extent of channel incision. Note that in the dry meadow reach (0 to 4000m downstream distance), the average ratio of the two-year flow depth to bank height is approximately 0.52. Subtracting the two-year flow depth from the bank height yields a rough estimate of channel incision; in the dry meadow this estimate of incision averages 0.86 +/- 0.04m. In the wet meadow reach (4000 to 9000m downstream distance), the two year flow exceeds the existing bank height, suggesting that if this reach has experienced any incision, the extent is much smaller than for the dry meadow reach.

Table 6. Two-year Flow Depth Analysis.

| Sample Cross-Sections: Downstream Distance (m) | Meadow Vegetation | Bank Height (m) | Maximum HEC- RAS 2-Year Flow Depth (m) | Ratio of 2 Year Flow Depth to Bank Height |
|---|------------------------------|------------------------|---|--|
| 2240 | dry | 1.5 | 0.5 | 0.33 |
| 2406 | dry | 1.8 | 0.6 | 0.50 |
| 2870 | dry | 2.0 | 1.3 | 0.65 |
| 3300 | dry | 1.6 | 1.0 | 0.63 |
| 3670 | dry | 1.6 | 0.8 | 0.50 |
| 4000 | wet | 1.4 | 1.7 | 1.20 |
| 6290 | wet | 0.8 | 1.3 | 1.60 |
| 7480 | wet | 0.8 | 1.1 | 1.40 |
| 9000 | wet | 0.8 | 0.8 | 1.00 |

Bed Shear Stress Analysis

Figure 17 compares the longitudinal variation in bed shear stress for the 1997 channel versus the “un-incised channel” for the 100-year return interval flow (2640 cfs). We used HEC-RAS to route the 100-year flow through the surveyed 1997 channel geometry, and then solved for bed shear stress at specific stations along the channel. We then used HEC-RAS to route the 100-year flow through the simulated channel we designed to just carry the two year flow, and solved for bed shear stress at cross-sections located at the same stations. This plot shows that shear stresses are on average approximately 46% greater for the 1997 channel than the simulated “un-incised” channel. This increase in shear stress associated with incision serves as a positive feedback on the incision process, and may serve to increase bed scour and thus destabilize banks to some extent.

Incision Impacts on Extent of Valley Inundation

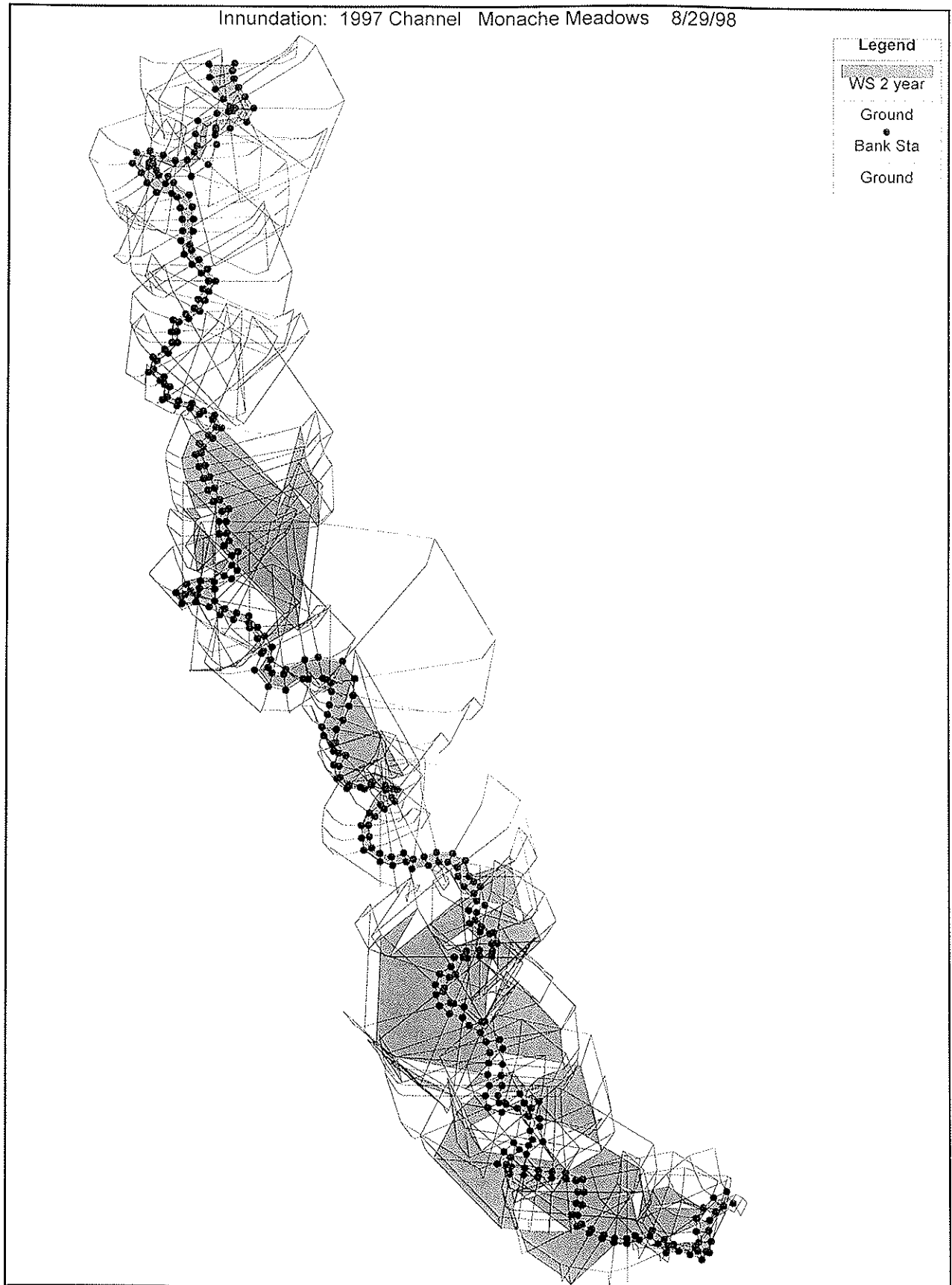
Figures 18 to 23 are three-dimensional plots of the extent of floodplain inundation in the meadows for the 1997 channel and the simulated un-incised channel, for discharges with

recurrence intervals of two, ten and 100 years. These inundation patterns indicate not only areas of overbank discharge and potential floodplain sediment deposition, but also areas of greater local groundwater availability. Our first observation is that the extent of inundation for the 1997 channel with the two-year flow roughly overlaps with the existing extent of wet meadow vegetation. We also observe that in contrast to the simulated un-incised channel and flood plain (which is completely inundated for the five-year flow and above), the existing channel configuration precludes complete inundation of the floodplain even during the 100-year event.

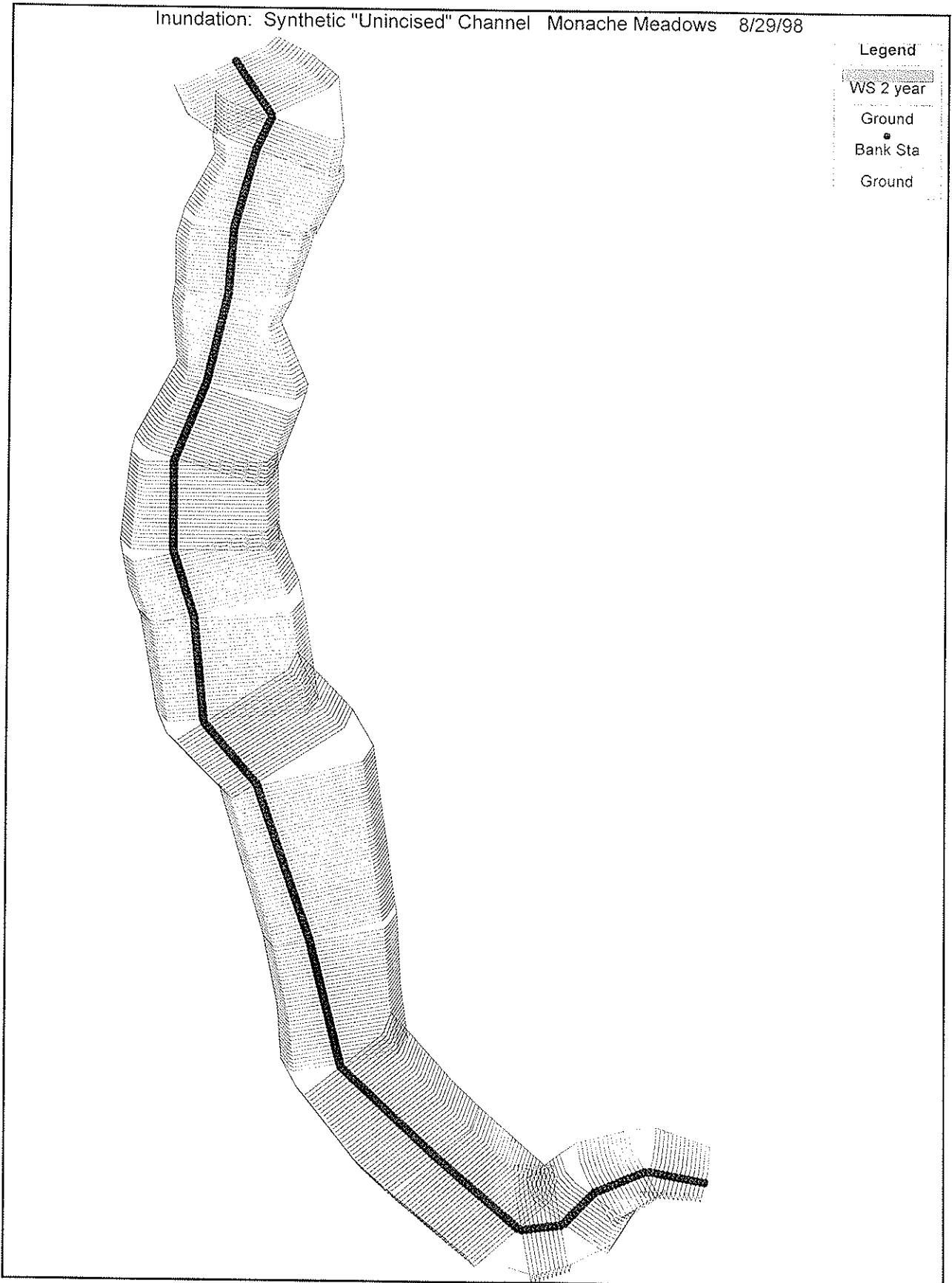
Currently, the meadows are only completely flooded at rare intervals, on the order of every hundred years. However, in the past the meadows may have been inundated as frequently as every 5 years. Incision has increased the channel capacity such that the enlarged river channel can now carry larger flow volumes without overflowing. Larger flow volumes in the channel result in higher bed shear stresses and greater transport of sediment, which in turn can lead to further channel incision. In addition, lower potential for floodplain inundation suggests that local groundwater availability has also been reduced. A first estimate would be that for the dry meadow reach, the local groundwater table has been depressed to the same extent as the channel bed has degraded, approximately 0.86m, with the potential result of having eliminated wet meadow vegetation from the floodplain.

As mentioned above, the “Transitional Meadow” categories appeared in the 1955 photographic image to be saturated and supporting dense stands of wet meadow vegetation. Perhaps the two kilometers of channel running through this reach has been experiencing some bed degradation over the last 40 years, with resultant reductions in wet meadow vegetation densities. Monitoring transitional meadow channel bed elevations and vegetation community composition over time could provide a test of the hypothesis outlined above.

Figure 18. Valley Inundation: 1997 Channel, 2-Year Flow



**Figure 19. Valley Inundation: "Un-incised Channel,"
2-Year Flow**



**Figure 20. Valley Inundation: 1997 Channel,
10-Year Flow**

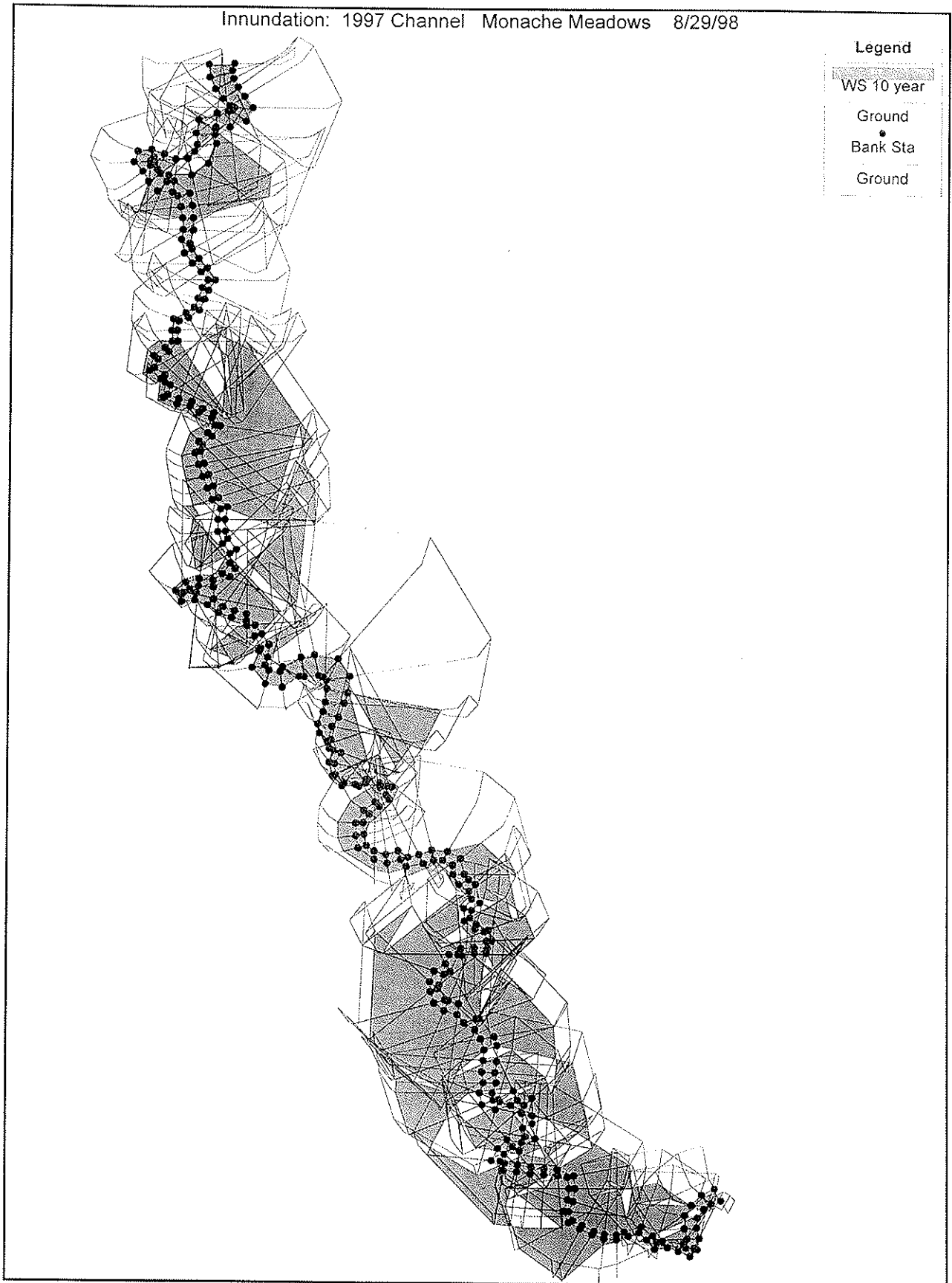


Figure 21. Valley Inundation: "Un-incised Channel,"
10-Year Flow

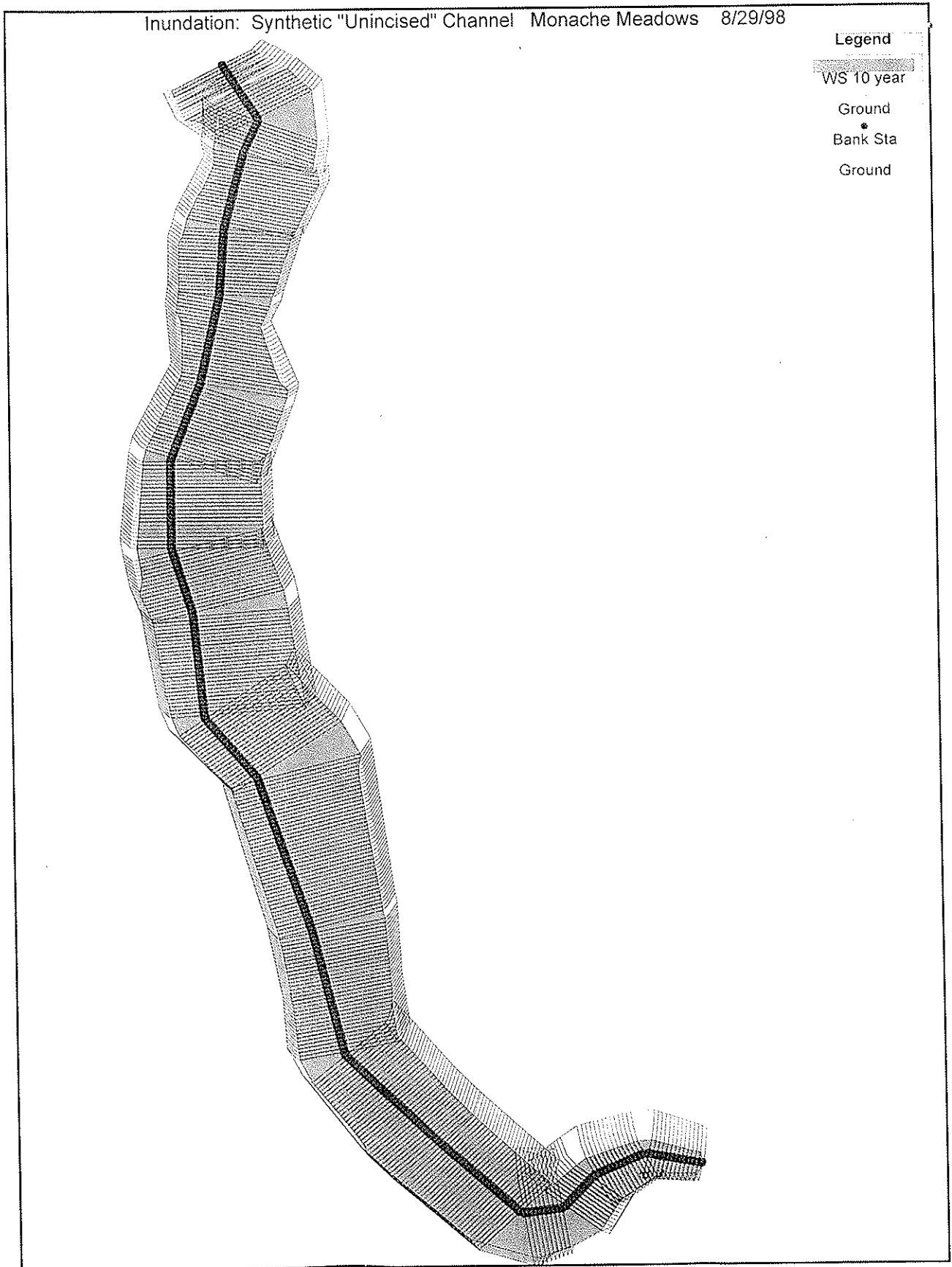
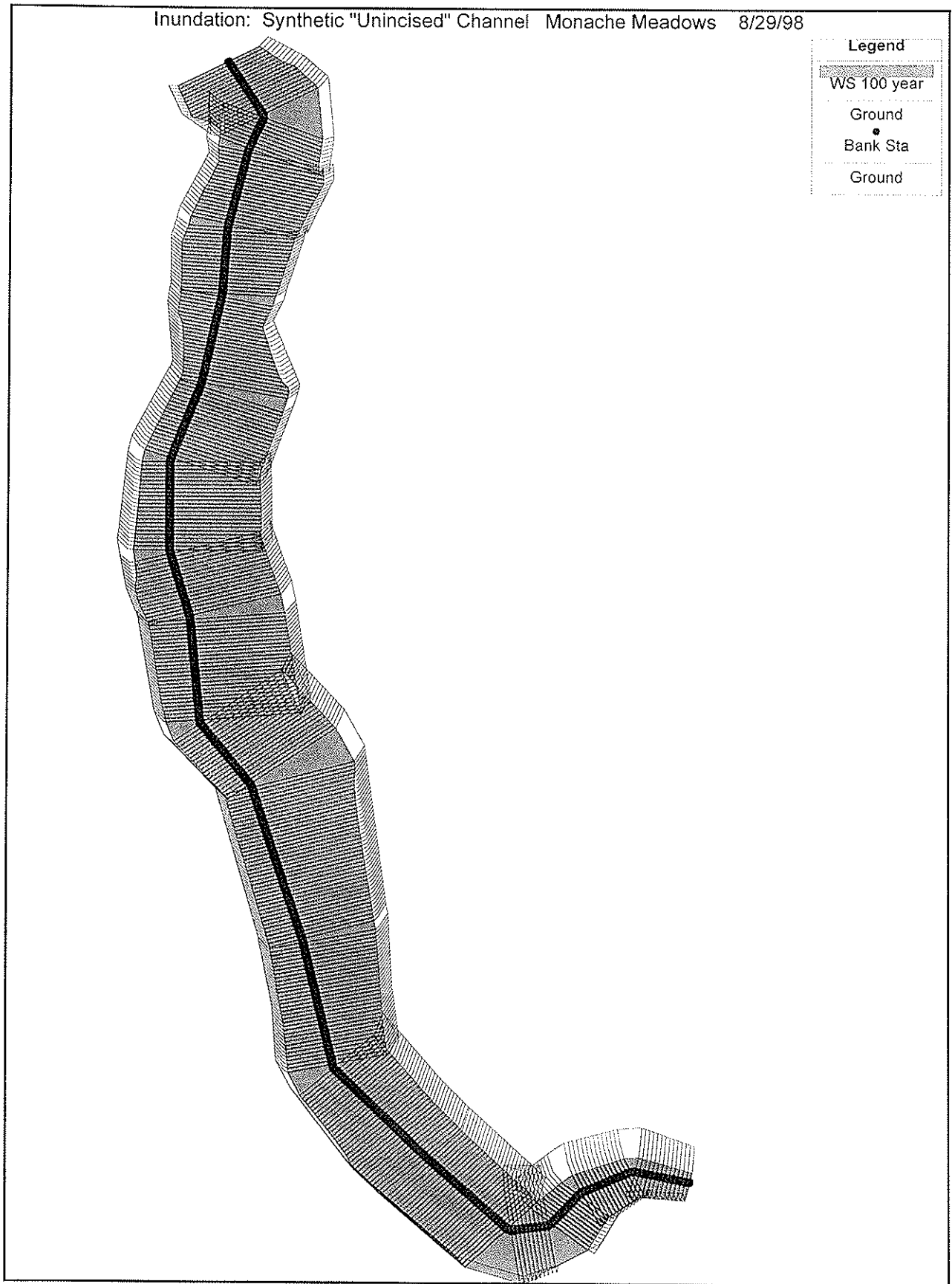


Figure 22. Valley Inundation: 1997 Channel, 100-Year Flow



**Figure 23. Valley Inundation: "Un-incised Channel,"
100-Year Flow**



DISCUSSION

Our results demonstrate how herbaceous riparian vegetation enhances the stability of a montane meadow stream, and illustrate how bank stability may be critical to maintaining the ecological health of the riparian ecosystem itself.

Our field observations indicate that banks with wet meadow vegetation tend to fail in cantilever mode. When stream flow undercuts a sedge-dominated bank, it produces a shelf, or cantilever, as thick as the root depth of the sedges (approximately 0.5 to 0.75m). Our calculations of cantilever stability using measured shear strength values for wet meadow banks show that cantilevers up to 1 meter in width (perpendicular to stream flow) can remain stable. While in place, the cantilever reduces flow shear at the base of the bank.

Further under-cutting may result in failure, but not necessarily detachment, cantilevers on wet meadow banks. Instead, these cantilevers may slump, draping the channel with a 0.75 m thick mat of fibrous roots, decayed organic matter and trapped fluvial sediments. Slump failure brings bank materials closer to the water table, making them increasingly favorable sites for colonization by hydrophytic vegetation. Increases in vegetation density increases the shear strength of the soil, potentially stabilizing failed blocks in place.

The erodibility of bank materials underlying the failed slump block is inconsequential if they are armored by dense stands of wet meadow vegetation. The flow instead must work against the densely rooted substrate generated by multiple seasons of vegetation growth. Field observations suggest that the only way to detach a slumped wet meadow block is exploit any tension cracks located between the failed block and the floodplain terrace.

Most of the dry meadow blocks that fail are rapidly undermined, broken up, and carried away by flow; we found few that were intact after detachment from the bank. Dry meadow banks fail in smaller, weaker blocks than the wet meadow. Furthermore, any strength provided by sagebrush or annual grasses is lost upon detachment and saturation, since dry meadow species cannot tolerate de-oxygenated conditions.

In the course of our shear strength measurements, we observed that sedge-colonized slump blocks tend to trap fluvial gravels that are coarser than typical floodplain sediments. Our strength measurements suggest that because these trapped gravels have a greater friction than finer substrates, they strengthen a vegetated soil matrix, creating a tough, gabion-like structure. This finding suggests that where vegetation contributes significantly to bank stability, bank erodibility may not directly depend on the fraction of cohesive silt-clays, as is commonly assumed (Schumm 1960).

The de-stabilizing effects of channel incision on streambank stability can be observed throughout California. Our analyses of the scale and consequences of incision at Monache Meadow allow us to weigh the relative significance of physical versus ecological factors influencing bank stability. Incision increases bank height, and thus: 1) increases the effective load on a bank; 2) increases the bed shear stress at the toe of the bank; and, 3) lowers the local water table, potentially altering vegetation types and densities.

We can use the geotechnical engineer's "factor of safety" to estimate the effect of channel incision on bank stability. The factor of safety is the ratio of stabilizing to destabilizing forces on a bank, with failure occurring at factors of safety less than one. The simplest model to calculate the factor of safety for a stream bank is Thorne and Abt's (1993), in which the factor of safety varies inversely with bank height. Thus, channel incision that increases the bank height

from 1.0 to 1.5 meters would decrease the factor of safety by one-third. The factor of safety also varies directly with bank shear strength or effective cohesion. The conversion of wet meadow to dry meadow via channel incision would reduce bank shear strength from roughly 45 to 15 kPa. This would reduce the factor of safety an additional 66%. Thus, the combined effects of incision reduce the factor of safety to less than a quarter of its original value. This rough calculation suggests that riparian vegetation conversion is a critical factor in patterns of bank erodibility observed at Monache Meadow.

One important bank stability factor remained outside the scope of this study. How do sediment supply and patterns of deposition influence channel stability, particularly in an incised channel? The dry meadow reach (0 to 4000m) displays a gradually decreasing slope in the longitudinal profile (figure 4), which indicates that this reach is a zone of potential sediment deposition. In this reach, thickly bedded sand strata are found in the floodplain terrace and abandoned channels, providing field evidence of episodic events of rapid deposition in the dry meadow reach. The channel in this reach is now incised, making overbank flows less frequent, and possibly causing sediment to be deposited on bars rather than the floodplain. Episodes of rapid bar accretion may accelerate stream migration through "bar push", the deflection of flow by a bar against the opposite bank (Dietrich pers. comm. 1998). Quantifying this effect would require measurements of the incoming sediment supply and very detailed estimates of deposition patterns. This type of analysis would also be required to estimate whether the channel at Monache Meadow will continue to incise.

PRINCIPAL FINDINGS

- Along the South Fork of the Kern River at Monache Meadow, streambanks with dry meadow vegetation (sagebrush and annual grasses) migrate, on average, seven times faster than streambanks with wet meadow vegetation (sedges and rushes).
- We calculate a dimensionless "erodibility coefficient" to characterize the susceptibility of stream bends to migration, independent of stream curvature. Our calculations show that the erodibility of the dry meadow streambanks is, on average, ten times greater than the erodibility of wet meadow streambanks.
- The reinforcement of bank soils by herbaceous riparian vegetation can increase the shear strength of soils by eight-fold. We measured shear strength increases of $0.09 (\pm 0.01)$ kPa per g/m^2 of above-ground dry biomass for rush-reinforced bar substrates and increases of $0.04 (\pm 0.01)$ kPa per g/m^2 of above ground dry biomass on sedge-reinforced slump blocks.
- Soil shear strength increases roughly linearly with the ratio of dry root biomass to dry soil mass in a given volume of soil. For our samples, we measured soil shear strength increases of $1020 (\pm 360)$ kPa per unit root biomass-soil mass ratio.
- Bank heights greater than one meter may preclude the establishment of hydrophytic herbaceous riparian vegetation on streambanks and adjacent floodplains at Monache Meadow. Channel incision beyond this threshold may trigger the conversion of the riparian zone from wet to dry meadow and significantly de-stabilize streambanks.

SUMMARY

At Monache Meadow, bank materials become finer and bank heights decrease with distance downstream. Both of these factors should enhance the geotechnical stability of banks and facilitate hydrophytic riparian vegetation establishment. The question we pose is which of these two factors is more significant in determining the stability of a montane meadow stream channel? Our results suggest that the up to tenfold variation in bank erodibility at Monache Meadows cannot be explained by physical factors alone: the presence or absence of riparian vegetation is critical to limiting rates of channel migration. Our results also suggest that a channel depth of roughly 1.0 m may represent a threshold between wet and dry meadow establishment. Incising the channel below this threshold may convert riparian vegetation from sedges or rushes to sage or annual grasses. These changes in vegetation communities destabilize streambanks, and may pose serious challenges to ecological restoration.

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